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Associations between High Temperature, Heavy Rainfall, and Diarrhea among Young Children in Rural Tamil Nadu, India: A Prospective Cohort Study

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BACKGROUND: The effects of weather on diarrhea could influence the health impacts of climate change. Children have the highest diarrhea incidence, especially in India, where many lack safe water and sanitation.

OBJECTIVES: In a prospective cohort of 1,284 children under 5 y of age from 900 households across 25 villages in rural Tamil Nadu, India, we examined whether high temperature and heavy rainfall was associated with increased all-cause diarrhea and water contamination.

METHODS: Seven-day prevalence of diarrhea was assessed monthly for up to 12 visits from January 2008 to April 2009, and hydrogen sulfide (H_2S) presence in drinking water, a fecal contamination indicator, was tested in a subset of households. We estimated associations between temperature and rainfall exposures and diarrhea and H_2S using binomial regressions, adjusting for potential confounders, random effects for village, and autoregressive-1 error terms for study week.

RESULTS: There were 259 cases of diarrhea. The prevalence of diarrhea during the 7 d before visits was 2.95 times higher (95% CI: 1.99, 4.39) when mean temperature in the week before the 7-d recall was in the hottest versus the coolest quartile of weekly mean temperature during 1 December 2007 to 15 April 2009. Diarrhea prevalence was 1.50 times higher when the 3 weeks before the diarrhea recall period included ≥ 1 d (vs. 0 d) with rainfall of >16.82 mm (95% CI: 1.12, 2.02), and 2.60 times higher (95% CI: 1.55, 4.36) for heavy rain weeks following a 60-d dry period. The H_2S prevalence in household water was not associated with heavy rain prior to sample collection.

CONCLUSIONS: The results suggest that, in rural Tamil Nadu, heavy rainfall may wash pathogens that accumulate during dry weather into child contact. Higher temperatures were positively associated with diarrhea 1–3 weeks later. Our findings suggest that diarrhea morbidity could worsen under climate change without interventions to reduce enteric pathogen transmission through multiple pathways. https://doi.org/10.1289/EHP3711

Introduction

Diarrhea is the fourth leading cause of death of children <5 y of age worldwide (Liu et al. 2012), and recurrent and prolonged episodes early in life have been linked to stunted growth and cognitive development (Checkley et al. 1998; Guerrant et al. 2013). Diarrhea is seasonal in many settings and all-cause diarrhea is associated with temperature and rainfall in both high- and low-income countries (Carlton et al. 2016; Checkley et al. 2000; Levy et al. 2016). Bacterial and protozoal diarrhea is also associated with increased temperature (Carlton et al. 2016). For bacterial pathogens that cause diarrhea, higher temperatures may promote bacterial population growth in stored food and drinking water, increasing the risk of food- and waterborne illnesses (D'Souza et al. 2004; McCabe-Sellers and Beattie 2004). Lower temperatures were associated with a higher incidence rate of rotavirus in two meta-analyses (Jagai et al. 2012; Levy et al. 2009); however, a meta-analysis of any viral diarrhea found no association with temperature (Carlton et al. 2016). Meta-analyses of rainfall have also revealed a positive association with all-cause diarrheal disease and an inverse association with rotavirus-caused diarrhea (Levy et al. 2009, 2016). Because climate change is expected to increase global temperature and the frequency and intensity of heavy rainfall events, understanding how weather influences diarrhea is increasingly important [Hales et al. 2014; Interagency Working Group on Climate Change and Health (U.S.) 2010].

In India, diarrhea causes an estimated 3.65% of disability adjusted life-years (DALYs) lost (7.1% of DALYs lost in children <5 y of age) (Murray et al. 2012). Despite this large burden, the contribution of climate-related stressors to child diarrhea in India is largely unknown. Evidence to date suggests there are strong seasonal patterns consistent with potential climate-related drivers: A study in Chennai, India, found increased diarrhea hospitalizations after heavy rainfall (Bush et al. 2014), and a study in Tamil Nadu found diarrhea seasonality and found that rainfall, but not temperature, increased diarrheal risk in rural populations (Kulinkina et al. 2016). Moreover, studies of the relationship between temperature, rainfall, and diarrhea risk across several low-income countries have mainly focused on populations that rely on surface water (e.g., springs, rivers, lakes) for drinking water (Adkins et al. 1987; Carlton et al. 2014, 2016; Luque Fernández et al. 2009; Jagai et al. 2012; Lama et al. 2004; Levy et al. 2016; Singh et al. 2001). In rural India, hundreds of millions of people obtain drinking water through systems that draw groundwater using tube wells, store it in village-level overhead storage tanks, and distribute it to standpipes through small, gravity-fed networks. In 2015, an estimated 85% of rural Indians had access to at least one of the following basic drinking-water sources: piped water, boreholes or tube wells, protected dug wells or springs, or packaged water (WHO and UNICEF 2017). It is, therefore, possible that rural Indian children are more protected from rainfall-driven changes in enteric pathogen transmission compared with populations that rely on surface drinking-water sources. Yet, several outbreak investigations in higher-income countries have traced diarrhea outbreaks to heavy rainfall-driven groundwater contamination (Auld et al. 2004; Gelting et al. 2005; Fong et al. 2007), and a study in Nigeria found increased borehole fecal pathogen contamination after rainfall, possibly due to poorly constructed or maintained boreholes (Kumpel et al. 2017).

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Our objective was to use coupled in-household child health surveillance and water quality data to estimate the relationship between temperature, rainfall, and child all-cause diarrhea risk in southern India and to investigate a possible causal pathway through water contamination. We combined climatological data with monthly longitudinal diarrhea surveillance in a community-based prospective cohort of children ≤ 5 y of age enrolled in a study of diarrhea following interventions to improve water supplies, sanitation, and hygiene in 25 rural villages in the Tiruchirappalli District of the State of Tamil Nadu in southern India (Arnold et al. 2010). We also tested for the presence of hydrogen sulfide (H_2S), a by-product of H_2S-producing bacteria and an indicator of fecal contamination, in stored household drinking water and samples collected from the primary water source for each village (Khush et al. 2013; McMahan et al. 2011). We sought to answer three research questions. *a*) Are high temperature and heavy rainfall associated with increased diarrhea prevalence in this study population? *b*) Are heavy rainfall and increased temperature associated with an increased prevalence of household water contamination? *c*) Are associations between heavy rainfall and diarrhea or water contamination modified by longer-term (60-d) rain trends?

Our rationale was that studies conducted in multiple locations have documented diarrheal disease outbreaks after heavy rain events (Smith et al. 1989; Trærup et al. 2011; Willocks et al. 1998; Yamamoto et al. 2000) and associations between increased rainfall and diarrhea (Adkins et al. 1987; Chou et al. 2010; Dewan et al. 2013; Seidu et al. 2013; Singh et al. 2001), with some studies reporting stronger associations when heavy rainfall occurred after a dry period (Bush et al. 2014; Carlton et al. 2014; Levy et al. 2016). Rainfall creates a muddy environment, which makes it more difficult to keep hands and household surfaces clean. If the mud contains human or animal feces, as is common in rural agricultural areas with poor sanitation, it could lead to diarrhea pathogen ingestion, especially among infants who exhibit frequent hand-to-mouth behavior (Mattioli et al. 2015; Ngure et al. 2013). If water flows over ground surfaces after a heavy rainfall, pathogens can be washed into watersheds or unprotected water sources (Dorner et al. 2006; Ferguson et al. 2003; Levy et al. 2016). It has been proposed that environmental flushing of feces that have accumulated during dry periods may explain stronger associations between heavy rainfall and diarrhea than when heavy rainfall follows a dry period (Bush et al. 2014; Carlton et al. 2014). The importance of individual transmission pathways likely varies across pathogens, climates, and water, sanitation, and hygiene (WASH) contexts, so prior study findings may not generalize to all regions. Climate change is predicted to increase temperature and the frequency and intensity of tropical cyclones in India, lending particular importance to the association between temperature, rainfall, and child diarrhea in this setting (Knutson et al. 2010; Kumar et al. 2006).

Methods

Study Setting and Design

The study was conducted in 25 rural villages outside the city of Tiruchirappalli in Tamil Nadu, India (Figure 1). The climate is tropical and hot with a rainy monsoon season from August to December, with the most rain occurring from September to November. The region is near sea level, with village elevations ranging from 74 m to 160 m. The primary water supply for all villages included in the study was groundwater that was pumped into elevated storage tanks. Water from storage tanks was then piped to

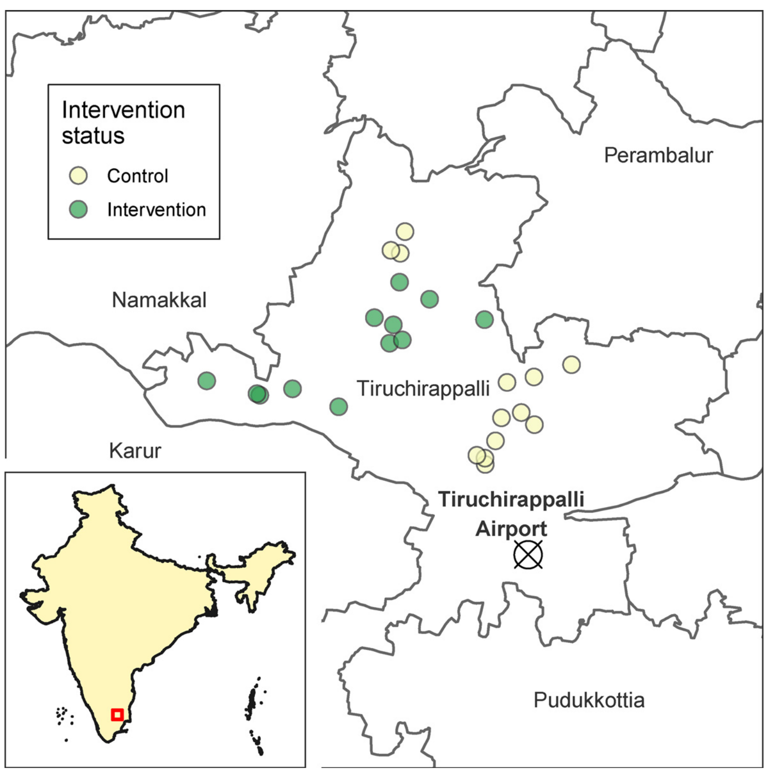


Figure 1. Map of study region with points marking the location of airport weather station and the intervention and control villages. The map shows the study area in the Tiruchirappalli region in southern India, with study villages plotted as points. The red box in the inset map of India shows where the study region was located within India, and the points are colored dark green for villages receiving the combination of WASH interventions and light yellow for matched control villages. The X-marked point indicates the location of the Tiruchirappalli Airport weather station, where rainfall and temperature were measured over the study period (1 December 2007 to 15 April 2009) and assumed to generalize to all the study villages.

public stand pipes, with several hundred people using each stand pipe as their primary water source through either public or private taps.

From 2003 to 2007, the non-governmental organizations Water.org and Gramalaya delivered a nonrandomized combination of WASH interventions to the 12 villages. Each village's WASH conditions were assessed through a participatory rural appraisal, and Gramalaya developed a combined intervention that was responsive to each village's assessment (Arnold et al. 2010). The main components of the WASH interventions were community mobilization campaigns to build private toilets, village standpipe water distribution improvements, primary school toilet improvements, primary school water tap improvements, subsidized loans for household tap or household latrine construction, and self-help groups to promote WASH and hygiene education. In late 2007, 13 control villages were matched to intervention villages with propensity score matching on pre-intervention characteristics (Arnold et al. 2010).

From 22 January to 16 March 2008, the study enrolled a random sample from each intervention village and matched control villages of 50 households with at least one child ≤ 5 y of age living in the household. If a village had <50 eligible households, then the sample included all eligible households. In unannounced visits, field staff visited once per month to assess child diarrheal disease symptoms for up to a total of 12 visits, with final visits occurring in April 2009. Child anthropometry was assessed on the first and last visit.

In the present analysis, we pooled data from intervention and control villages because there were no significant differences in child growth or diarrhea between children living in enrolled households from the intervention and control villages based on the data gathered across the monthly visits (Arnold et al. 2010). The intervention improved village WASH conditions based on measurements collected in the study population. Compared with control villages, intervention villages had higher levels of toilet ownership (57% intervention vs. 26% control) and lower levels of reported open defecation after intervention delivery, although open defecation was common in both (77% intervention vs. 88% control; Arnold et al. 2010).

Ethics

Data collection followed protocols approved by the institutional review boards (IRBs) at the University of California, Berkeley, and Sri Ramachandra Medical College, Chennai, India. Primary caregivers of children ≤ 5 y of age were enrolled in the study if they provided informed consent on behalf of their children. Female literacy was sufficiently low in the study area that limiting enrollment to literate caregivers would have threatened the validity of the study. If the child's primary caregiver was literate, she provided written consent, otherwise caregivers provided oral consent as approved by the local IRB. Oral consent was obtained by field staff by reading out the IRB-approved consent script to eligible participants in the local language (Tamil), and a list of the households that provided oral consent to participate was maintained by the field supervisors.

Outcome Definitions

At enrollment, study staff collected information on household demographics, assets, and WASH conditions. Study fieldworkers conducted up to 12 monthly follow-up visits at each household to query primary caregivers about symptoms of diarrhea in each eligible child during the 7 d before the visit. Eligible children were classified as having had diarrhea during the 7-d recall period if they had three or more loose or watery stools within 24 h or had one or more stools with visible blood (Arnold et al. 2013). For households with multiple eligible children ($n = 357$), fieldworkers assessed diarrhea symptoms separately for each child. Fieldworkers collected samples of stored drinking water from a random, rotating subset of households during monthly survey rounds, starting in the third round (Arnold et al. 2010). Participant households were randomly allocated into four groups. Two of the groups were measured in rounds 3 and 5, and the other two groups were measured in rounds 4 and 6. In survey rounds 7–12, households in one of the four groups were tested. Each household's drinking water was tested between one and four times over the study period, and 48.9, 48.1, 48.9, 46.6, 25.0, 23.8, 23.8, 22.2, 25.2, and 23.7% of the 900 enrolled households had their drinking water tested during rounds 3–12, respectively. Fieldworkers also collected samples from the primary water sources for each village in each survey round, starting in the third round. Villages had on average 3.1 (± 1.47) primary water sources, which were sampled on average 9.0 (± 2.1) times.

Water samples were tested for the presence of H_2S using the HiH_2S test kit (HiMedia K020; HiMedia). Samples were identified as positive for H_2S if they turned black within 24 h of incubation with the H_2S detection reagents at room temperature.

Exposure Definitions

Daily rainfall and temperature measurements were gathered contemporaneously by study personnel from the Tiruchirappalli International Airport weather station operated by the India Meteorological Department from 1 December 2007 to 15 April 2009 (the study period). The distance from the airport to the 25 study villages ranged from 17 to 55 km. The minimum and maximum temperature on each day was recorded by minimum and maximum thermometers housed in a Stevenson screen. The daily mean temperature was defined as the average of the minimum and maximum temperature for each day, and the mean temperature during each 7-d period was defined as the average of the daily mean values during that time period. Associations between temperature and the 7-d prevalence of diarrhea were lagged by 1, 2, or 3 weeks such that the temperature lagged by 1 week was the average daily temperature over the 7 d before the 7-d recall period for diarrhea symptoms (8–14 d before the study visit), whereas 2- and 3-week lagged temperatures were based on average daily temperatures 15–21 d and 22–28 d before the study visit. Lagged weekly mean temperature was evaluated as a continuous variable and as a categorical variable according to quartiles of temperature based on the distribution of 7-d averages (as defined above) from 1 December 2007 to 15 April 2009.

Precipitation during each day was measured with a self-recording rain gauge. Each 7-d period was classified as having heavy rainfall if it included at least 1 d with ≥ 16.82 mm of precipitation (where 16.82 mm is the 80th percentile of daily rainfall on days with >0 mm of precipitation during 1 December 2007 to 15 April 2009) and as not having heavy rainfall otherwise. Exposure to heavy rainfall was lagged 1, 2, or 3 weeks such that exposure to heavy rainfall lagged by 1 week was based on ≥ 1 d (vs. 0 d) with rainfall ≥ 16.82 mm during the 7-d before the start of the 7-d diarrhea recall period (i.e., 8–14 d before the study visit.)

Statistical Methods

We plotted exposure–outcome curves to visualize potential nonlinear trends. We fit cubic splines using generalized additive models over the range of observed prior weekly mean temperature and total weekly rainfall accumulation and over observed weekly rainfall accumulation stratified by 60-d rain trends (Hastie and Tibshirani 1986). The degrees of freedom (df) used in each cubic spline were chosen over a range of 1–10 as the degrees of freedom that maximized 10-fold cross-validated prediction accuracy. We estimated Bayesian 95% simultaneous confidence intervals (CIs) around the fitted curves (Nychka 1988). Weekly mean 24-h rainfall accumulation is $\log_e$-transformed because although most weeks had <1 mm average rainfall, there were a few outlier heavy rainfall weeks. We estimated diarrhea prevalence ratios (PRs) between children exposed to quartiles of weekly mean temperature, with the lowest quartile as the reference value, and between children exposed and not exposed to heavy rainfall events prior to the 7-d diarrhea recall period. Weekly rainfall accumulation was natural log-transformed because although most weeks had <1 mm average daily rainfall, there were a few outlier heavy rainfall weeks. The degrees of freedom used in each cubic spline was chosen over a range of 1–10 as the degrees of freedom that maximized 10-fold cross-validated prediction accuracy.

We estimated both unadjusted and adjusted PRs with binomial regressions (log-link), and models included random effects for village membership to control for potential within-village correlation, and an autoregressive-1 error term on the study week of the household visit to account for potential temporal autocorrelation in diarrhea and weather. Values for the study week ranged from 1 (first study week) for outcomes assessed between 22 and 27 January 2008, the first 7 d of household visits, to 65 for outcomes assessed after 12 April 2009, the final week of household visits. We did not account for the nonindependence of observations for children from the same household because multilevel models including random effects for both village and household membership as well as an autoregressive-1 error term for the study week of data collection did not converge for some estimates, possibly due to the low prevalence of diarrhea. The models were fit using penalized quasi-likelihood using the glmmPQL () function from the "MASS" library in R (Breslow and Clayton 1993; Venables and Ripley 2002). We estimated both unadjusted PRs and PRs adjusted for potential confounders. We repeated this analysis to estimate the associations between heavy rainfall and temperature and H_2S presence in stored household drinking water and between heavy rainfall and H_2S presence in a village's primary drinking-water sources. Because the HiH_2S test only detects the presence of H_2S in stored water on the day of collection, the lagged weather exposures were offset 1 week later than the corresponding lags for the 7-d diarrhea recall period; that is, 1-week lagged weekly mean temperature was averaged over the 1–7 d prior to the household visit for the H_2S outcome but over the 8–14 d prior to the household visit for the child diarrhea outcome.

The following baseline survey variables were selected as potential confounders because they were plausibly associated with diarrhea risk and were missing for ≤50% of participants: child sex, child age, current breastfeeding status; intervention group; maternal age, literacy, education, and employment status; number of people in household; household water source; reported open defecation from household member; household latrine ownership; indicators for presence of water, soap, ash, towel/cloth, sink, or flies at the household handwashing station; indicators for household participation in a community group, credit finance group, or agricultural work; indicators for if the household had electricity, a bank account, a covered kitchen, a ventilated kitchen, a thatched roof, or a dirt floor; stove type; cooking fuel used; family-owned land; family-owned home; indicator for if family was from a scheduled caste; and separate indicators for ownership of a dog or cat, buffalo, cow, ox, calf, goat, chicken, cell phone, television, motorcycle or scooter, bicycle, or mosquito net; and village-level open defecation rate, which was estimated from the rate of reported open defecation from study household members (Table 1). Mean temperature during the lagged week of heavy rainfall exposure and mean rainfall during the lagged week of average temperature exposure were also considered as potential confounders for associations with rainfall and temperature, respectively. Covariates were selected separately for each adjusted model based on a likelihood ratio $p < 0.2$ for the association between the potential confounder and the outcome, and therefore the set of variables included in each regression model could vary across outcomes and lag periods. In addition, to reduce the risk of over-specification (Arnold et al. 2010; Peduzzi et al. 1996), each model included a maximum of one covariate per 10 outcome events (e.g., no more than six covariates for a model that included 60 cases of diarrhea), with potential covariates eliminated according to p-value rank. Missing covariate data were replaced with the median value for continuous variables and were modeled using a missing indicator term for categorical variables. Mother's age was the only continuous variable with missingness, with 17 of 900 households missing mother's age. We also conducted complete-case analyses and report the results in the supplementary material.

In a sensitivity analysis, we estimated the association between heavy rainfall and diarrhea prevalence using the 70th percentile (9.20 mm) and 90th percentile (42.18 mm) of rainfall on days with >0 mm precipitation during 1 December 2007 to 15 April 2009 as the heavy rain threshold instead of the 80th percentile threshold used in the primary analysis. We also estimated the associations between heavy rainfall and 7-d diarrhea prevalence or H_2S presence after stratifying by tertiles of precipitation during the 60 d before the lagged exposure week (i.e., for 1-week lagged heavy rainfall exposure during the 8–14 d before the study visit, we stratified by average rainfall during the 15–74 d before the study visit). Tertile categories for these analyses were based on the distribution of average daily rainfall for all days in the study period.

We conducted all statistical analysis using R (version 3.5.1; R Development Core Team). All data files, analysis R scripts, and figure code are available through Open Science Framework (https://osf.io/2pu3d/).

Results

Study Population

We analyzed 14,254 diarrhea prevalence measurements from 1,284 children ≤5 y of age from 900 households across the 25 villages (median age in months at enrollment: 30.7, range: 0.9–62.7); (Table 1). There was an average of 11.1 (±2.48) longitudinal observations per child, and 1,220 children (95%) completed the full 12-month follow-up. We conducted H_2S tests on 3,025 stored household drinking-water aliquots randomly sampled across study rounds 3–12, and on 695 aliquots of villages' primary water sources collected across study rounds 3–12. Households had on average 4.8 (±1.3) persons and 1.4 (±0.6) children included in the study, latrines were present at 41.6% of households; open defecation was reportedly practiced in 82.8% of households; 49.2% of households had a handwashing station with soap; and 28.8% of households used a private tap as the primary water source while 63.8% of households used a public tap (standpipe) and the remainder used a well (Table 1).

Outcome and Exposure Measurements

During the study, caregivers reported 259 diarrhea cases. The 7-d prevalence of diarrhea was recorded for 14,259 person-weeks among the 1,284 children included in the analysis, for a 7-d prevalence of 1.8%. Five of the 14,259 measurements collected occurred more than a week after the original study ceased recording weather data and were dropped from the analysis. All 5

Table 1. Summary of demographic, socioeconomic, and water, sanitation, and hygiene characteristics of the study population at baseline measurement.

Study characteristics	n (%) or mean ± SD
Observations (n)	14,254
Children (n)	1,284
Households (n)	900
Household water samples (n)	3,025
Villages (n)	25
Village water samples (n)	695
Diarrhea cases (n)	259
Days of weather data (n)	502
Pre-intervention covariates	
Received intervention	636 (49.5)
Did not receive intervention	648 (50.5)
Child[a]	
Sex	
Female	635 (49.5)
Male	645 (50.2)
Missing	4 (0.3)
Breastfeeding[b]	
Currently breastfeeding	2,308 (16.2)
Not currently breastfeeding	11,946 (83.8)
Maternal[c]	
Age	26.8 ± 5
Literacy	
Yes	741 (82.3)
No	158 (17.6)
Missing	1 (0.1)
Education	
None	131 (14.6)
Primary school	117 (13)
Middle school	246 (27.3)
High school	277 (30.8)
Higher secondary	91 (10.1)
College	28 (3.1)
Graduate School	8 (0.9)
Missing	2 (0.2)
Works	
Yes	434 (48.2)
No	451 (50.1)
Missing	15 (1.7)
Household[d]	
People in household	4.8 ± 1.3
Study children in household	1.4 ± 0.6
Household sanitation	
Reported open defecation	
Yes	745 (82.8)
No	155 (17.2)
Own private latrine	
Yes	374 (41.6)
No	526 (58.4)
Household water and handwashing	
Primary source	
Private Tap	259 (28.8)
Public Tap	574 (63.8)
Private Well	28 (3.1)
Public Well	39 (4.3)
Handwashing station	
Flies present	338 (37.6)
Flies absent	562 (62.4)
Water present	564 (62.7)
Water absent	336 (37.3)
Soap present	443 (49.2)
Soap absent	457 (50.8)
Ash present	409 (45.4)
Ash absent	491 (54.6)
Towel/cloth present	168 (18.7)
Towel/cloth absent	732 (81.3)
Sink present	244 (27.1)
Sink absent	656 (72.9)
Household characteristics	
Community group participation	
Yes	420 (46.7)
No	480 (53.3)
Credit finance group participation	
Yes	310 (34.4)
No	590 (65.6)
Parent works in agriculture	
Yes	573 (63.7)
No	327 (36.3)
Electricity	
Yes	810 (90)
No	90 (10)
Bank account	
Yes	195 (21.7)
No	705 (78.3)
Scheduled caste	
Yes	117 (13)
No	783 (87)
Covered kitchen	
Yes	736 (81.8)
No	162 (18)
Missing	2 (0.2)
Ventilated kitchen	
Yes	571 (63.4)
No	37 (4.1)
Not known	292 (32.4)
Thatched roof	
Yes	220 (24.4)
No	680 (75.6)
Dirt floor	
Yes	617 (68.6)
No	283 (31.4)
Owns home	
Yes	836 (92.9)
No	64 (7.1)
Owns land	
Yes	853 (94.8)
No	47 (5.2)
Stove type	
Three stones	454 (50.4)
Kerosene	295 (32.8)
Gas	145 (16.1)
Other	4 (0.4)
Missing	2 (0.2)
Cooking fuel	
Wood	787 (87.4)
Liquid petrol gas	89 (9.9)
Kerosene	24 (2.7)
Household assets	
Owns buffalo	
Yes	29 (3.2)
No	871 (96.8)
Owns cow	
Yes	361 (40.1)
No	539 (59.9)
Owns ox	
Yes	37 (4.1)
No	863 (95.9)
Owns calf	
Yes	244 (27.1)
No	656 (72.9)
Owns goat	
Yes	295 (32.8)
No	605 (67.2)
Owns chicken	
Yes	149 (16.6)
No	751 (83.4)

[a]Out of 1,284 children.
[b]Out of 14,254 observations because breastfeeding indicators are time-varying.
[c]Out of 900 mothers or primary caregivers.
[d]Out of 900 households.
[e]Out of 25 villages.
[f]Estimated from rate of reported open defecation from study households.

Table 1. (*Continued.*)

Study characteristics	*n* (%) or mean ± SD
Owns dog or cat	
Yes	99 (11)
No	801 (89)
Cell phone	
Yes	294 (32.7)
No	606 (67.3)
Television	
Yes	588 (65.3)
No	312 (34.7)
Motorcycle/scooter	
Yes	228 (25.3)
No	672 (74.7)
Bicycle	
Yes	687 (76.3)
No	213 (23.7)
Mosquito net	
Yes	120 (13.3)
No	780 (86.7)
Village[e]	
Open defecation rate[f]	83.02% ± 13.20%

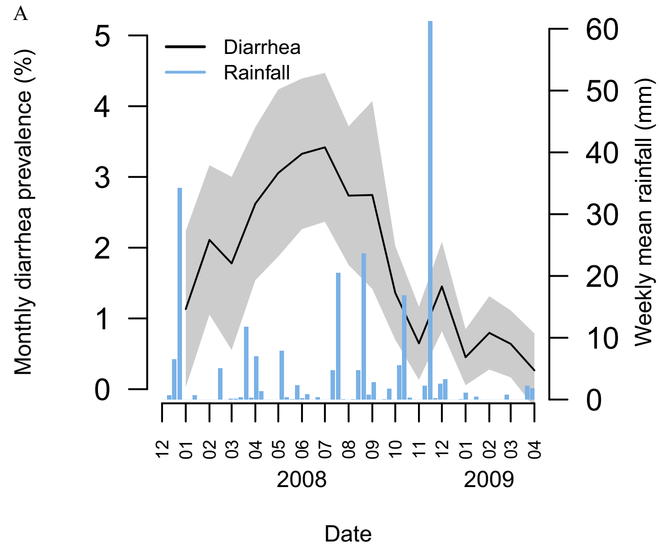
measurements were of children who did not have diarrhea in the week prior to measurement.

The study period (1 December 2007 to 15 April 2009) consisted of mostly dry days with periodic spikes in heavy rainfall: 389 of 502 d had no rain, with an overall mean of 3.3 mm (±16.1) of rain per day (Figure 2A). The heaviest rainfall was 172.6 mm on 19 December 2007. The study period was rainier than historical averages for the Tiruchirappalli Airport (e.g., rainfall in 2008, the only full year during the study period: 1,328 mm, 1971–2000 average: 862 mm), but there was a typical seasonal trend, with a less rainy May–August monsoon period (496 mm, 1971–2000 average: 229 mm) and a rainier September–November monsoon period (641 mm, 1971–2000 average: 479 mm) (India Meteorological Department; http://www.imd.gov.in/section/climate/extreme/tiruchirapalli2.htm). Fifty-seven percent of the 7-d recall periods were preceded by a 7-d period that included any rainfall, and 18% were preceded by a week that included a heavy rainfall event (at least 1 d with rainfall >16.82 mm) (for the second and third weeks before the 7-d recall period, 60% and 58% had any rain, and 16% and 16% had heavy rain, respectively). There were no missing weather exposure data in the primary analyses, but there was missing information on longer-term (60-d) rainfall trends for 609, 856, and 987 of 14,254 observations for the 1-, 2- and 3-week lagged exposures, respectively, and these observations were dropped from the analysis. The missingness arose because the daily rainfall records began on 1 December 2007, whereas the earliest 60-d rainfall average period began on 26 November 2017, 88 d prior (60-d averaging period, plus 21 d for the 3-week lag, plus the 7-d diarrhea recall period) to the first diarrhea surveillance visit on 22 January 2008.

Weekly average temperature had seasonal trends (Figure 2B), with a 26.8°C (±1.9) average from October to March, and a 31.0°C (±1.4) average from April to September, with a maximum of 32.2°C in April and a minimum of 25.4°C in January. The hottest day had a 34°C average and a 40.3°C maximum. The coldest day had a 22°C average and 16.8°C minimum.

Associations between Temperature, Diarrhea, and Water Quality

Semiparametric spline fits illustrated a nonlinear, convex increase in 7-d diarrhea prevalence as temperature increased in the 1, 2, and 3 weeks prior to the 7-d diarrhea recall period (Figure 3A). The cutoffs between quartiles of weekly mean temperature were 26.1, 28.1, and 30.5°C. The highest vs. lowest quartile of mean weekly temperature ($\geq$30.5°C vs. $\leq$26.1°C) was positively associated



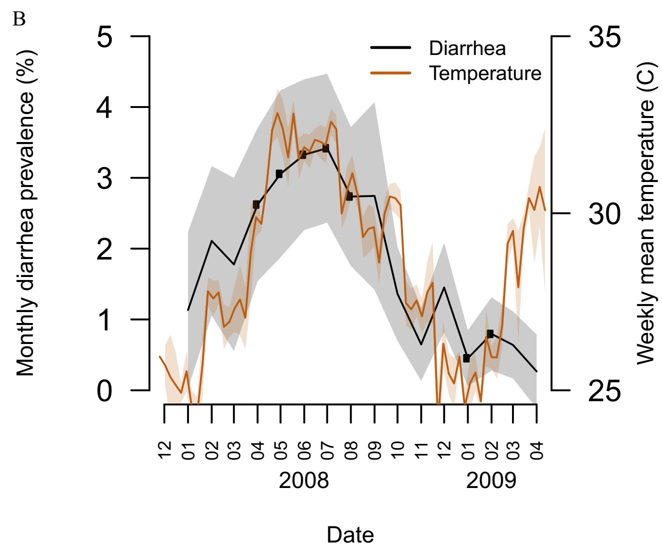


Figure 2. Diarrhea prevalence, rainfall, and temperature over the study period. (A) Mean 7-d prevalence of diarrhea during each month [with 95% confidence interval (CI) band] and weekly rain accumulation over the study period (December 2007–April 2009). (B) Mean 7-d prevalence of diarrhea during each month (with 95% CI band) and weekly mean temperature over the study period.

with diarrhea for all lag periods: the adjusted PR was 2.95 (95% CI: 1.99, 4.39) with a 1-week lag, 2.84 (95% CI: 1.95, 4.15) with a 2-week lag, and 3.39 (95% CI: 2.31, 4.98) with a 3-week lag (Figure 3B; see also Table S1). Risk increased by quartile of temperature: Compared with the first quartile, adjusted 1-week lagged PRs increased monotonically for the second [PR = 1.01 (95% CI: 0.64, 1.60)], third [PR = 1.74 (95% CI: 1.15, 2.64)], and fourth [PR = 2.95 (95% CI: 1.99, 4.39)] quartiles (Figure 3B; see also Table S1). There was no difference in inference between estimates from models that only adjusted for village membership and study week (autoregressive term) and models that additionally adjusted for potential confounders, or between models with missing indicator terms and complete-case models (see Table S1).

There were 3,025 tests of stored household drinking water for H_2S, of which 2,551 samples (84.3%) tested positive. No quartile of temperature was significantly different from the lowest quartile and estimated prevalence ratios were close to the null (Figure 3C; see also Table S2).

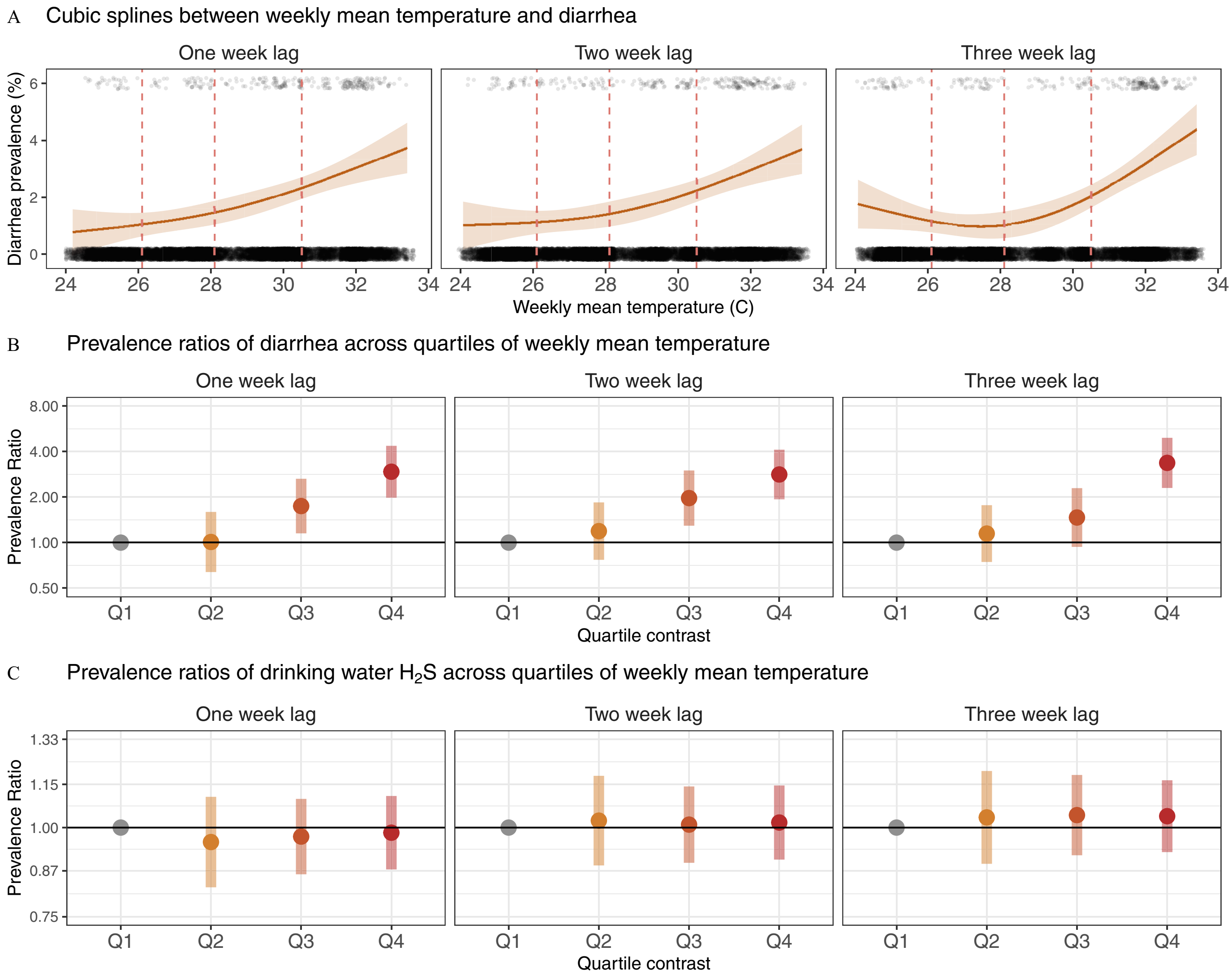


Figure 3. Relationships between weekly mean temperature and 7-d prevalence of diarrhea among children ≤ 5 in and H_2S in stored household drinking water 1, 2, or 3 weeks prior to the 7-d diarrhea recall period, Tamil Nadu, India, 2008–2009. (A) Adjusted associations between weekly temperature and the 7-d prevalence of diarrhea (95% simultaneous confidence bands) estimated with cubic splines, fit with 3 df. The vertical dashed lines in the temperature plots mark the 25th, 50th, and 75th percentiles of temperature over the study period. Observed diarrhea cases are plotted as points at the top of each plot and observed noncases are plotted as points at the bottom of each graph. Points are jittered for visibility. The weekly mean temperature is lagged 1 (left panel), 2 (middle panel), and 3 weeks (right panel) prior to the start of the 7-d diarrhea recall period. (B) Adjusted prevalence ratios (with 95% CI) for diarrhea according to quartiles (Q) of weekly mean temperature lagged 1, 2, and 3 weeks prior to the start of the 7-d diarrhea recall period. Q1–Q4 indicate mean weekly temperature quartiles 1–4, with the first (lowest) quartile of temperature used as the reference level to calculate prevalence ratios, and using 26.1, 28.1, and 30.5°C as the cutoffs between the quartiles. Prevalence ratios were estimated with binomial regressions (log-link) models that included random effects for village membership and an autoregressive-1 error term on the study week of the household visit and potential confounders selected via likelihood ratio tests. The selected covariates were child age; intervention group; primary water source; current breastfeeding status; indicators for household participation in a community group, credit finance group, or agriculture; indicators for if the household had electricity, a thatched roof, a bank account, or a dirt floor; indicators for presence of water, soap, ash, towel/cloth, sink, or flies at the household handwashing station; indicators for ownership of a dog or cat, ox, television, motorcycle or scooter, or mosquito net; and indicator for reported open defecation from a household member. The model with a 3-week lag period was additionally adjusted for mean weekly rainfall during the week of temperature exposure. (See Table S1 for numeric data.) (C) Adjusted prevalence ratios (with 95% CI) for the presence of H_2S in household stored drinking-water samples according to quartiles of weekly mean temperature lagged 1, 2, and 3 weeks prior to the start of the 7-d diarrhea recall period. Q1–Q4 indicate mean weekly temperature quartiles 1–4, with the first (lowest) quartile of temperature used as the reference level to calculate prevalence ratios, and using 26.1, 28.1, and 30.5°C as the cutoffs between the quartiles. Prevalence ratios were estimated with binomial regressions (log-link) models that included random effects for village membership and an autoregressive-1 error term on the study week of the household visit and potential confounders selected via likelihood ratio tests. The selected covariates were mean weekly rainfall during the week of temperature exposure; child sex; intervention group; primary water source; maternal age and education; indicators for presence of soap, ash, or sink at the household handwashing station; indicators for if the household has a bank account, a ventilated kitchen, or a latrine; primary cooking fuel used; family-owned land; family-owned home; indicator for if family is from a scheduled caste; indicators for ownership of buffalo, goat, television, or motorcycle or scooter; and village-level open defecation rate, estimated from rate of reported open defecation from study household. (See Table S2 for numeric data.)

Association between Heavy Rainfall, Diarrhea, and Water Quality

There was no consistent spline shape between increasing weekly mean rainfall and diarrhea prevalence, with an estimated concave shape with a 1- or 2-week lag and a convex shape with a 3-week lag (Figure 4A). The 7-d prevalence of diarrhea increased after a heavy rain event, especially 3 weeks prior to the 7-d recall period, with adjusted PRs of 1.05 (95% CI: 0.78, 1.42) for the 1-week lag, 1.16 (95% CI: 0.86, 1.58) for the 2-week lag, and 1.50 (95% CI: 1.12, 2.02), for the 3-week lag (Figure 4B; see also Table S3). Estimates from unadjusted models and complete-case models were similar to those from models adjusted for covariates with missing data indicators (see Table S3). In the sensitivity analysis of the threshold used to define heavy rainfall events, estimates from unadjusted models using the 70th or 90th percentiles of rainfall across days with >0 mm of precipitation to define heavy rainfall were consistent with estimates from models using the 80th percentile except that the confidence intervals estimated from the 3-week lag

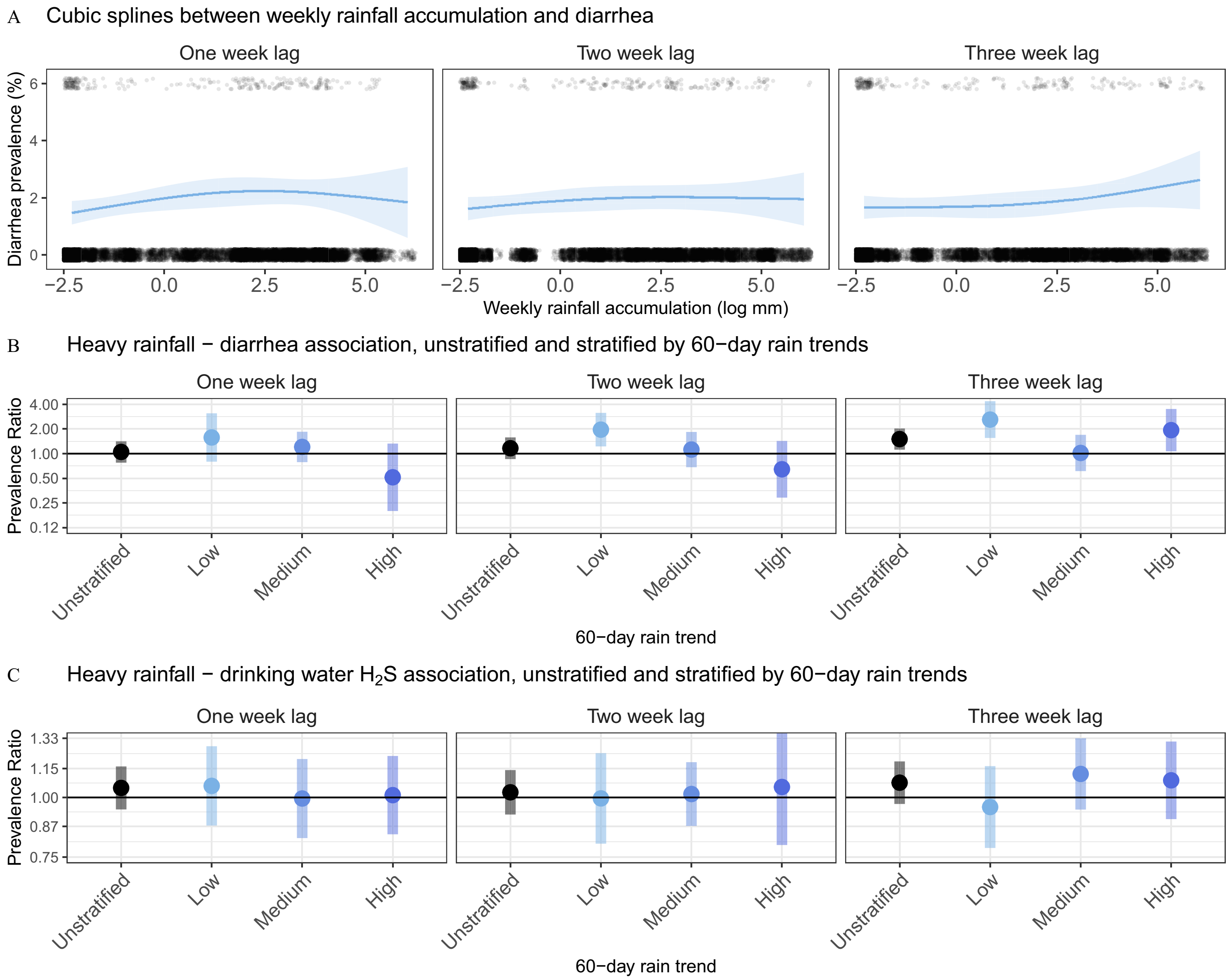


Figure 4. Seven-day prevalence of diarrhea among children ≤5 in relation to weekly rainfall and heavy rain events, and the prevalence of H_2S in stored household drinking water 1, 2, or 3 weeks prior to the 7-d diarrhea recall period in relation to heavy rain events, Tamil Nadu, India, 2008–2009. (A) Adjusted associations between natural log-transformed weekly rainfall accumulation (log-mm) and the 7-d prevalence of diarrhea (95% simultaneous confidence bands) estimated with cubic splines, lagged 1 (left panel), 2 (middle panel), and 3 weeks (right panel) prior to the start of the 7-d diarrhea recall period. Observed diarrhea cases are plotted as points at the top of each plot and observed noncases are plotted as points at the bottom of each graph. Points are jittered for visibility. The splines are fit with 3, 4, and 3 df for the left, center, and right panel, respectively. (B) Adjusted prevalence ratios (with 95% CI) for diarrhea in relation to weeks with heavy rain events (≥1 d of rainfall above the 80th percentile of daily accumulation during the study period vs. weeks with no heavy rainfall) for all weeks (unstratified) and stratified by low, medium, and high tertiles of rainfall accumulation during the 60-d prior to the week of exposure, which was lagged 1 (left), 2 (middle), and 3 (right) weeks prior to the start of the 7-d diarrhea recall period. Prevalence ratios were estimated with binomial regressions (log-link) models that included random effects for village membership and an autoregressive-1 error term on the study week of the household visit and potential confounders selected via likelihood ratio tests. (See Table S3 for numeric data and model covariates.) (C) Adjusted prevalence ratios (with 95% CI) for the presence of H_2S in household stored drinking-water samples in relation to weeks with heavy rain events (>1 d of rainfall above the 80th percentile of daily accumulation) for all weeks (unstratified) and stratified by low, medium, and high tertiles of rainfall accumulation during the 60-d prior to the week of exposure, which was lagged 1, 2, and 3 weeks prior to the start of the 7-d diarrhea recall period. Prevalence ratios were estimated with binomial regressions (log-link) models that included random effects for village membership and an autoregressive-1 error term on the study week of the household visit and potential confounders selected via likelihood ratio tests. (See Table S4 for numeric data and model covariates.)

models crossed the null when using the 70th or 90th percentiles (see Figure S1).

A heavy rainfall event before the 7-d recall period (using the 80th percentile as the threshold for heavy rain) was positively associated with H_2S-based evidence of stored household drinking water contamination, but with 95% CIs overlapping the null [adjusted 1-week lag PR = 1.05 (95% CI: 0.94, 1.16); 2-week lag PR = 1.03 (95% CI: 0.92, 1.14); and 3-week lag PR = 1.07 (95% CI: 0.97, 1.19)]; (Figure 4C; see also Table S4). Unadjusted PRs and complete-case PRs were very similar to the adjusted estimates from models with missing data indicators (see Table S4). We tested 695 samples collected from the primary drinking-water source for the study villages, and 407 (58.6%) were positive for H_2S, consistent with bacterial contamination. A heavy rainfall event 1–7 d before sample collection was associated with evidence of contamination (adjusted PR = 1.38; 95% CI: 1.10, 1.73), but not heavy rainfall events 8–14 d earlier (PR = 1.14, 95% CI: 0.97, 1.34) or 15–21 d earlier (PR = 0.88; 95% CI: 0.73, 1.04); (see Table S5).

Modification by Rainfall in the Previous 60 d

There was evidence of effect modification of the heavy rainfall–diarrhea association by longer-term (60-d) rainfall trends (Figure 3B; see also Table S3). When a heavy rainfall event occurred after a dry period (60-d rainfall in the lowest tertile, $\leq$1.39 mm), the 7-d prevalence of diarrhea increased, especially with a 2- or 3-week time-lag, with adjusted PRs of 1.57 (95% CI: 0.80, 3.10) for the 1-week lag, 1.96 (95% CI: 1.22, 3.14) for the 2-week lag, and 2.60 (95% CI: 1.55, 4.36) for the 3-week lag (Figure 4B; see also Table S3). In contrast, heavy rainfall events were not consistently associated with the 7-d prevalence of diarrhea after 60-d periods with rainfall in the second or third tertile (>1.39–3.48 and >3.48 mm, respectively). Estimates from unadjusted models and complete-case models were similar to those from models adjusted for covariates with missing data indicators (see Table S3).

Associations between heavy rain events and H_2S prevalence ratios in stored household drinking water did not show clear differences when stratified by average rainfall during the previous 60 d (Figure 4C; see also Table S4). Heavy rainfall during the 1–7 d before sample collection was not associated with the presence of H_2S in the primary village water source after a 60-d period of low rainfall [PR = 0.87 (95% CI: 0.59, 1.30)] or medium rainfall [PR = 0.95 (95% CI: 0.64, 1.40)], and was positively, but not significantly, associated evidence of bacterial contamination following 60-d periods with high rainfall [PR = 1.27 (95% CI: 0.84, 1.92] (see Table S5).

Discussion

Key Findings

In this cohort of children < = 5 y of age in rural Tamil Nadu, the prevalence of diarrhea was associated with higher quartiles of average temperature during the first, second, and third weeks before the 7-d diarrhea recall period. The overall association between a heavy rainfall event (vs. no heavy rainfall event) and the 7-d prevalence of diarrhea varied among the three lag periods, but was consistently positive when the heavy rainfall occurred after a 60-d dry period. Fecal contamination of household drinking-water samples, as indicated by a positive H_2S test, was not clearly associated with mean temperature or heavy rainfall during the 1–3 weeks before the measurement.

Interpretation

The association between temperature and diarrhea prevalence in this population is consistent with past studies in similar settings. Our results are similar to those from studies in Bangladesh (Ali et al. 2013; Dewan et al. 2013; Hashizume et al. 2008) and other tropical regions (Luque Fernández et al. 2009; Trærup et al. 2011; Zhang et al. 2008) that reported positive associations between diarrhea and increasing ambient temperatures. Our findings for quartiles of average weekly temperatures (based on the average of the daily minimum and maximum temperatures during each 7-d period) are not directly comparable to estimates based on temperature modeled as a continuous variable, but results did suggest a monotonic increase in the prevalence of diarrhea with increasing temperatures in previous weeks.

We found evidence that heavy rainfall events were associated with higher diarrhea risk in the following 1–3 weeks, consistent with findings from prior studies in other populations (Bush et al. 2014; Carlton et al. 2014; Levy et al. 2016). Heavy rainfall events were positively associated with diarrhea risk across 1-, 2-, and 3-week time lags, but only a 3-week lag was statistically significant [adjusted PR = 1.50 (95% CI: 1.21, 2.02)]; (see Table S3). A study in northern Ecuador reported that diarrhea was associated with heavy rainfall 2 weeks prior, but not 1 week prior (Carlton et al. 2014), and a study in northern Ghana reported that maximum rainfall lagged 2- and 6-weeks, but not 4-weeks prior, was significantly associated with diarrhea (Seidu et al. 2013). Thus, although heavy rainfall has been associated with diarrhea in several studies, the lag between heavy rainfall and diarrhea may be location specific, perhaps because of differences in local transmission dynamics or the incubation periods of the predominant pathogen taxa. Secondary transmission of diarrheal disease could also account for the association with the 3-week lagged heavy rainfall, but secondary transmission also would be expected to increase diarrhea after a 2-week lag (Carlton et al. 2014). The sensitivity analysis of heavy rainfall classification found a consistent increase in diarrhea prevalence regardless of heavy rain classification thresholds or lag period, but variation in estimates across scenarios was small relative to confidence interval width (see Figure S1).

When heavy rainfall followed a 60-d period of low average rainfall, the adjusted PR for diarrhea following a 7-d period with (vs. without) a heavy rain event ranged between 1.57 (95% CI: 0.80, 3.10) for a 1-week lag and 2.60 (95% CI: 1.55, 4.36) for a 3-week lag, whereas PRs were inconsistent when heavy rainfall occurred after periods of medium or high average rainfall (Figure 4B). A possible explanation for this finding is that human and animal feces that accumulate in the environment during dry periods may be flushed by heavy rainfall into contact with children. These findings are consistent with a study in Chennai, India, of hospital admissions for diarrhea (Bush et al. 2014) and a study in Ecuador of child diarrhea ascertained based on caregiver recall (Carlton et al. 2014), which both reported increased diarrhea when heavy rainfall occurred after dry periods compared with when heavy rainfall occurred after wet periods.

Our findings on the associations between heavy rainfall and all-cause diarrhea are consistent with prior studies; however, there is limited information on the environmental pathways through which heavy rain might increase diarrhea risk, and, to our knowledge, our analysis of H_2S prevalence in village source water and household drinking water is novel. Heavy rainfall can flush feces directly into surface water, but villages in the study area stored groundwater in overhead tanks that should theoretically have been protected from contamination through this route. However, heavy rainfall can directly contaminate groundwater, and studies in Nigeria have reported more frequent microbial contamination of borehole groundwater samples in the rainy season and of samples collected near poor sanitation facilities (Auld et al. 2004; Fong et al. 2007; Gelting et al. 2005; Kumpel et al.

2017). Poorly constructed or maintained boreholes with cracks in the cement aprons or linings are potentially vulnerable to the intrusion of fecal contamination from the surface during rainfall, but we believe that it is more likely that other mechanisms contributed to the association between heavy rainfall and diarrhea in our study population.

Stored household drinking water in study households had more frequent detection of H_2S than village source standpipes [2,551 of 3,025 positive household samples (84%) versus 407 of 695 village samples (59%)], which suggests that drinking water was contaminated between the source and point-of-use, possibly by dirty hands dipped into the stored water (Khush et al. 2013). Heavy rainfall 3 weeks prior to sample collection was associated with a higher prevalence of H_2S detection in stored drinking water (89.2% vs. 83.3% positive), although the prevalence ratio confidence interval overlapped the null and there was a larger difference in the prevalence of H_2S in village source water after heavy rainfall 1-week prior (69.2% vs. 56.6% positive), but neither association had a clear pattern of modification by 60-d rain trends. It is possible that in our study population, heavy rainfall increased the risk of child diarrhea by contaminating drinking water at the village source, whereas the larger increase in diarrhea when a heavy rain event followed a dry period may have been caused by the flushing of accumulated pathogens into contact with children. Children could ingest feces washed into mud through hand-to-mouth behavior with muddy hands, or muddy conditions could lead to more food contamination.

Limitations

Temperature and rainfall measurements taken at the Tiruchirappalli Airport were assumed to apply to all villages because weather data were not gathered at the village level. This assumption may be more reasonable for temperature than for rainfall, which can be more heterogeneous than temperature at provincial scales. The uncertainty in the true weather at each village is a limitation of this study, and exposure misclassification may have led to bias. Low temporal resolution in both the exposures and outcomes used in analyses may have led to bias and reduced precision.

There is potential for residual confounding, particularly if there were unmeasured time-varying confounders with seasonal patterns that matched rainfall and influenced diarrheal disease or H_2S prevalence. In addition, although included covariates had low or no missingness (<2%), the indicator method of handling missing categorical data can lead to bias, even if the missingness is random (Greenland and Finkle 1995). We also did not model multiple children living in the same household with a household-level random effect in a multi-level model, which could affect the precision of our estimates.

This study was based on diarrhea data collected over a 15-month period from January 2008 to April 2009, which is a shorter period than used in similar studies; therefore, we cannot examine interannual variability of the observed patterns (Bush et al. 2014; Carlton et al. 2014; Curriero et al. 2001; Thomas et al. 2006). The study period was also rainier than historical averages for the study area.

Reported diarrhea was not confirmed in a laboratory, where causal pathogens could have been identified. The higher diarrhea prevalence during hotter periods suggests that many of the diarrhea cases were caused by bacterial, protozoal, or parasitic infections rather than viral pathogens. Findings from past studies suggest that lower temperatures increase the transmission of viral diarrhea (D'Souza et al. 2008; Konno et al. 1983), whereas higher temperatures are associated with bacterial diarrhea (Ali et al. 2013; Dewan et al. 2013; D'Souza et al. 2004; Luque Fernández et al. 2009; Trærup et al. 2011; Zhang et al. 2008). A meta-analysis of factors influencing rotavirus infections, a common viral diarrhea pathogen, found evidence of a protective effect of high temperature, but the investigators did not identify any studies that examined associations between rainfall and rotavirus diarrhea (Levy et al. 2016). Therefore, information on specific pathogens involved in individual cases would help clarify the effects of temperature and rainfall on diarrhea in future studies.

Without laboratory confirmation, reported diarrhea is subject to reporting bias. We would not expect diarrhea reporting to be differential by temperature or rainfall, but it is possible that the lower diarrhea prevalence in January–April 2009 compared with January–April 2008 could have resulted from caregivers underreporting illness as the study progressed (Schmidt et al. 2011). Overall, the child diarrhea prevalence of 1.8% was low compared with a previous trial in the region that found a 10% prevalence of chronic diarrhea (Rahmathullah et al. 1991), and the relatively small numbers of cases reduced the precision of our estimates and limited power to detect associations, especially in the subgroup analysis of heavy rainfall stratified by 60-d rain trends.

The H_2S test only detects the presence of H_2S in water, so it does not capture any increase in fecal contamination in already-contaminated water sources. As a binary measure, the H_2S test may not be adequately powered to detect small changes in concentration due to rainfall, and most stored household drinking-water samples were positive across all sampling visits (>75%), so an increase in H_2S after heavy rain would have been difficult to detect. Therefore, the observed null association between heavy rainfall and household stored drinking-water H_2S prevalence may only provide evidence that there was no major increase in fecal contamination after heavy rain, rather than that there was no increase in fecal contamination. However, a previous analysis of this cohort found a strong relationship between increased prevalence of H_2S in water samples and the concentration of coliform bacteria in the water samples (Khush et al. 2013). In addition, a key limitation of the H_2S test is that it is not a direct measure of pathogen presence, only of fecal contamination. Thus, the test does not indicate whether the fecal contamination contains bacterial pathogens, viral pathogens, or no pathogens. However, we would expect a stronger association between heavy rainfall and prevalence of H_2S in stored household drinking water if heavy rain was flushing appreciable amounts of feces from the environment and into drinking water, and if heavy rainfall increased fecal contamination of drinking water, there would be an increased likelihood of contamination with diarrhea pathogens.

A potential driver of the patterns observed in rainfall, water contamination, and diarrheal disease that warrants further research could be time-varying levels of host immunity. Children who were infected and became ill after a heavy rain event may still be infected but not experience clinical illness after exposure to the same pathogens during subsequent heavy rain events. This hypothesis could also explain higher diarrheal disease risk after the low tertile of 60-d rain because the children may have been less recently exposed to pathogens transported by rainfall and, therefore, have waning immunity. The higher risk of H_2S contamination in drinking water after heavy rainfall was modest, with 95% CIs overlapping the null, but the association was consistently positive and did not vary significantly over the strata of 60-d rain trends. Potentially, heavy rain events that follow higher levels of rain do not increase diarrheal disease risk due to host immunity; nevertheless, asymptomatic individuals may still shed pathogens into the environment and contaminate drinking-water sources after heavy rain.

Generalizability

Our findings require confirmation, but if they are valid, they might be generalizable to other rural populations in southern

India with similar weather patterns and WASH conditions. Regions with low open defecation could have a smaller pathogen reservoir in the environment, and regions without monsoon deluges may not receive enough precipitation to cause the surface flow that washes enteric pathogens into human contact. However, the WASH characteristics of study villages are similar to much of rural India (Kumar and Das 2014), a region with a very high population and burden of diarrhea, so our findings might be relevant to a large portion of the children at risk of weather-driven diarrheal disease. An interesting future study could explore the geography, WASH conditions, or predominant pathogens of low-income countries where high temperature and heavy rainfall are not associated with increased diarrhea.

Conclusions

We found positive associations between high temperature, heavy rainfall, and all-cause diarrhea in children ≤ 5 y of age and evidence suggesting that drinking water contamination may not be the primary infection pathway in rural Tamil Nadu. The association between heavy rain events and diarrhea was stronger when heavy rain followed a 60-d dry period, which suggests an infection mechanism whereby rain flushes accumulated environmental contaminants into human contact. This occurred despite the population's reliance on groundwater and standpipe distribution systems, which should be more protected from flushed contamination than surface water. Heavy rain had a weak association with a higher prevalence of H_2S-producing bacteria, an indicator of fecal contamination, in the village water sources and household drinking water, but there was no effect modification of either association by longer-term rain trends. This suggests that in southern India heavy rainfall may influence diarrhea pathogen ingestion by the child through other routes in addition to contaminated drinking water. As climate change models project increasing temperature and extreme rainfall events in India, child morbidity from diarrhea could worsen in the absence of interventions that reduce enteric pathogen transmission through multiple pathways.

Acknowledgments

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